# Dynamic range for bone conduction ultrasound

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## 1 Introduction

Since Gavreau [1] reported that ultrasound could be perceived by bone conduction, controversial discussions have surrounded the concept of the auditory perception of ultrasound. Particular attention has been paid to its perception mechanism and to whether or not the profoundly hearing-impaired can detect ultrasound and discriminate ultrasound modulated by different speech sounds. Consideration is being given to the possibility of using ultrasound hearing aids as an alternative to cochlear implant. Pertaining to the peripheral mechanism of ultrasound perception, the following hypotheses were suggested by Dieroff and Ertelsu [2]. 1) Ultrasonic perception as a result of inadequate stimulation of particular sections of the hearing system [3]. 2) Ultrasonic perception as a result of adequate stimulation of particular sections of the hearing system. The second hypothesis was classified into two categories: the existence of rudimentary ultrasonic receptors [4,5] and the generation of subharmonic vibrations in the range of audio frequency through non-linearities in the transmission path of ultrasound. However, despite later studies, the peripheral mechanism of ultrasonic perception has not been clarified.

There has been no report on the central mechanism of ultrasound perception, i.e., which sensory area in the brain is activated by ultrasound stimulation; the auditory area receiving it as a sound sensation, the somatosensory area processing it as a vibro-tactile sensation, or areas specific to ultrasound processing, before Hosoi et al. [6] reported that bone-conducted ultrasound could be perceived as a sound sensation. They observed that bone-conducted ultrasound activated the auditory cortex generating the N1m component similar to that of normal sound with magnetoencephalography (MEG). They also measured the mismatch magnetic fields which reflect neural activities detecting acoustic differences, with ultrasound modulated by different speech sounds.

Regarding the application of ultrasound to the hearing-impaired, Lenhardt et al. [7] reported that bone-conducted ultrasonic hearing was capable of supporting frequency discrimination and speech detection in not only normal but also elderly hearing-impaired and profoundly deaf subjects. They suggested that ultrasonic bone conduction hearing may potentially be used as an alternate communication channel in the rehabilitation of hearing disorders.

In addition to such interesting issues, bone-conducted ultrasound hearing has some characteristics different from normal sound perception. In this experiment, we have studied the effect of the intensity of stimuli and inter-stimulus intervals (ISI) for ultrasonic sensation as compared with normal sound sensation. We measured the amplitudes of N1m elicited by bone-conducted ultrasound and air-conducted normal sound stimuli using MEG in order to estimate the loudness growth in ultrasonic hearing.

## 2 Methods

We studied seven volunteers (six right handed and one left handed) with normal hearing. Voluntary consent was obtained from the subjects prior to participation in the experiment. The stimuli were bone-conducted ultrasonic tone bursts of 28-33kHz and air-conducted tone bursts of 2kHz. The frequency of the bone-conducted ultrasound test stimuli was set at each subject's easiest listening frequency. We also measured the thresholds of bone-conducted ultrasound and air-conducted tone bursts for each subject before the examination in order to determine 0dBSL. The duration of stimuli was 30ms, including rise and fall times 10ms. Air-conducted tone bursts were delivered to the left ear through a plastic tube and bone-conducted ultrasound was delivered to the left sternocleidomastoid using a ceramic vibrator. The magnetic fields around the head were measured with a 122-channel whole-head magnetometer (Neuromag122$^{TM}$) in a magnetically shielded room. First, we studied the effect of the intensity level on N1m. The intensity level of bone-conducted ultrasound was set at 0, 10 and 20dBSL and that of air-conducted tone bursts was set at 0, 20 and 40dBSL with 4.0s ISI. Second, we studied the effect of ISI on N1m using 0.5, 1.0, 2.0 and 4.0 ISI with 20dBSL intensity level. We measured the N1m amplitude for bone-conducted ultrasound stimuli using the sensor on which the largest amplitude of N1m was recorded among the sensors located to the right hemisphere when bone-conducted ultrasound of 20dBSL was given to the subject.

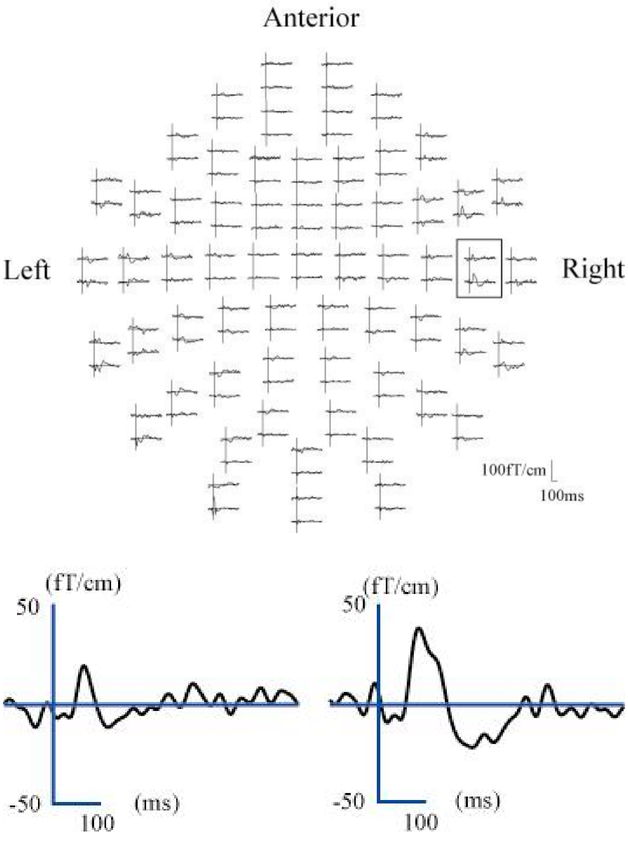

Figure 1: *Magnetic responses of a subject for 30kHz bone-conducted tone burst. (Intensity: 20dBSL, ISI: 4s) The two responses in the lower part came from a pair of sensors which is shown with the rectangle in the upper part.*

For air-conducted tone bursts of 2kHz, we adopted the sensor which showed the largest amplitude of N1m when 40dBSL tone bursts was given to the subject. The magnitude of N1m for each subject was expressed as a relative value by defining the amplitude of 20dBSL as a reference value. We observed the relationships between the amplitude of N1m and both intensity of stimuli and ISI.

## 3 Results

We could observe N1m for bone-conducted ultrasound in six of the seven subjects. MEG responses of a subject for bone-conducted ultrasound and air-conducted tone bursts of 2kHz are shown in Fig.1, 2. Fig.3 shows the relationships between amplitude of N1m and the intensity level for bone-conducted ultrasound and air-conducted tone bursts of 2kHz.

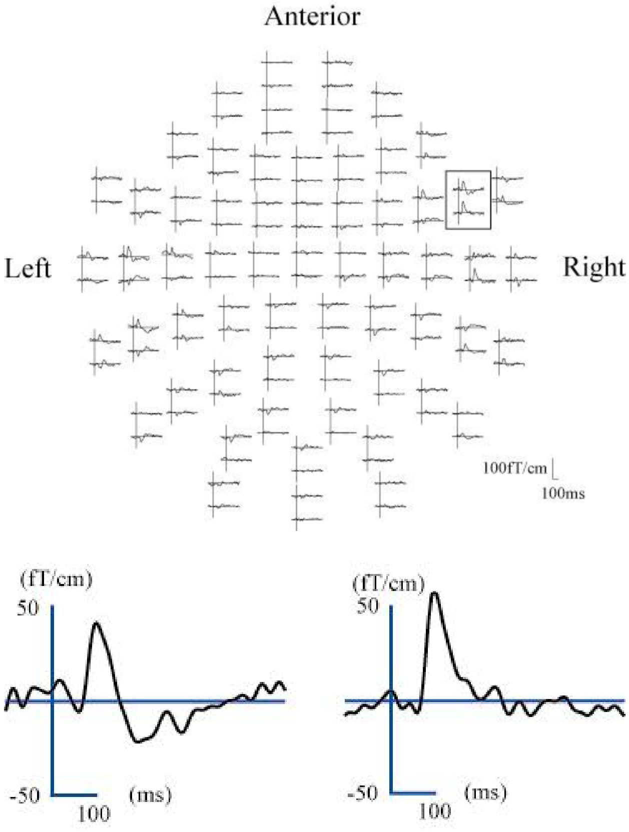

Figure 2: *Magnetic responses of a subject for 2kHz air-conducted tone burst. (Intensity:40dBSL, ISI: 4s) The two responses in the lower part came from a pair of sensors which is shown with the rectangle in the upper part.*

The mean values among six subjects of N1m elicited by bone-conducted ultrasound at 10 and 0dBSL were 0.60 and 0.07 respectively. That elicited by air-conducted tone bursts at 40 and 0dBSL were 1.29 and 0.46 respectively. Judging from Fig.3, the loudness growth of bone-conducted ultrasound is more conspicuous than that of air-conducted tone bursts.

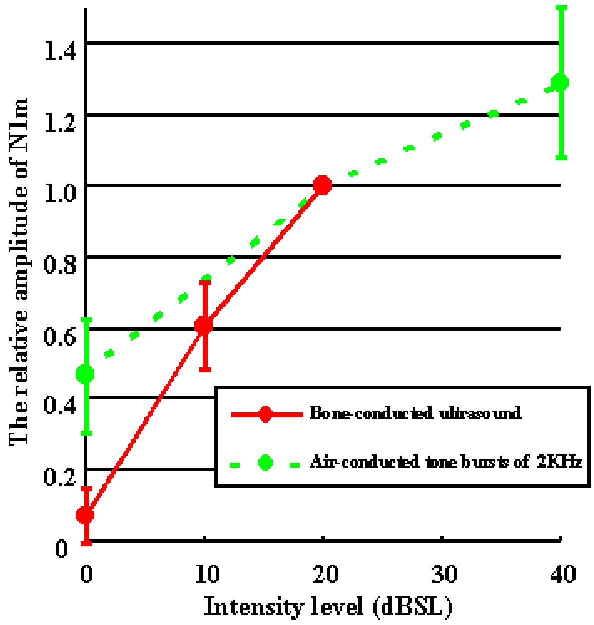

Figure 3: *The relationships between the amplitude of N1m and the intensity level for bone-conducted ultrasound and air-conducted tone bursts of 2kHz.*

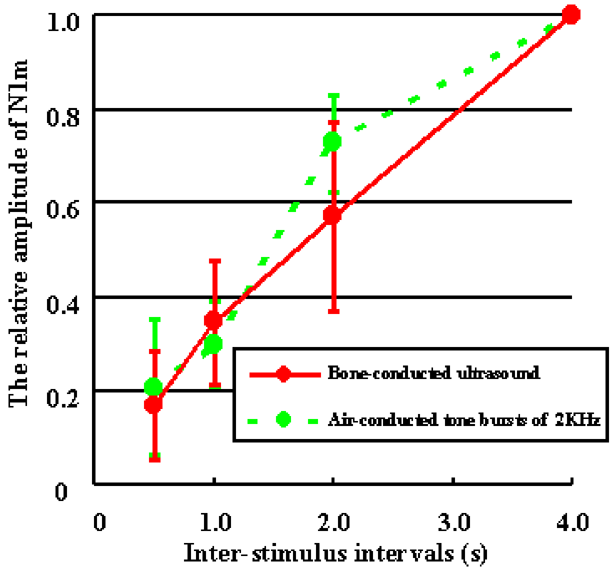

Figure 4: *The relationships between the amplitude of N1m and ISI level for bone-conducted ultrasound and air-conducted tone bursts of 2kHz.*

Fig.4 shows the relationships between the amplitude of N1m and ISI. The longer the ISI, the larger the amplitude of N1m, for both bone-conducted ultrasound and air-conducted tone bursts. There was no obvious difference between these two stimuli.

## 4 Discussion

Because of the limitation of output power of the ceramic vibrator, N1m elicited by bone-conducted ultrasound was not saturated as shown in Fig.3. Therefore, the dynamic range of N1m could not be determined. However, the rate of amplitude growth of N1m for bone-conducted ultrasound was higher than for the air-conducted tone bursts, when the intensity of the stimuli increased from 0dBSL to 20dBSL. This result is congruous with that of the psycho-acoustical experiment concerning loudness growth for bone-conducted ultrasound as compared with normal sound. On the other hand, there was no clear difference between bone-conducted ultrasound and air-conducted normal sound regarding the effect of ISI.

Ohyama et al. [8] investigated the mechanism of ultrasonic perception using electrocochleography (EcochG) in guinea pigs. According to their report, the loudness growth of ultrasound was more conspicuous than of normal sound, judging from the action potentials(AP) amplitude of EcochG. For instance, the amplitude of AP in EcochG elicited by a click at 106dBSPL was almost equal to that elicited by ultrasound at 20-30dBSL. They also reported that the sound perception in the ultrasonic region could be performed by the inner hair cell system without any enhancement or modulation of the outer hair cell system because there was little change in the EcochG elicited by ultrasound in kanamycin-poisoned guinea pigs [9].

Our experimental result, i.e., rapid loudness growth of bone-conducted ultrasound seems reasonable if the inner hair cells are related to ultrasound perception without any influence of the outer hair cell system as Ohyama reported. Regarding the similar result of ISI between bone-conducted ultrasound and normal sounds, the transmission pathway for ultrasound might be similar to that for normal sounds after the inner hair cell system. However, the existence of plural pathways for bone-conducted ultrasound hearing cannot be denied by this experiment.

## Acknowledgements

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